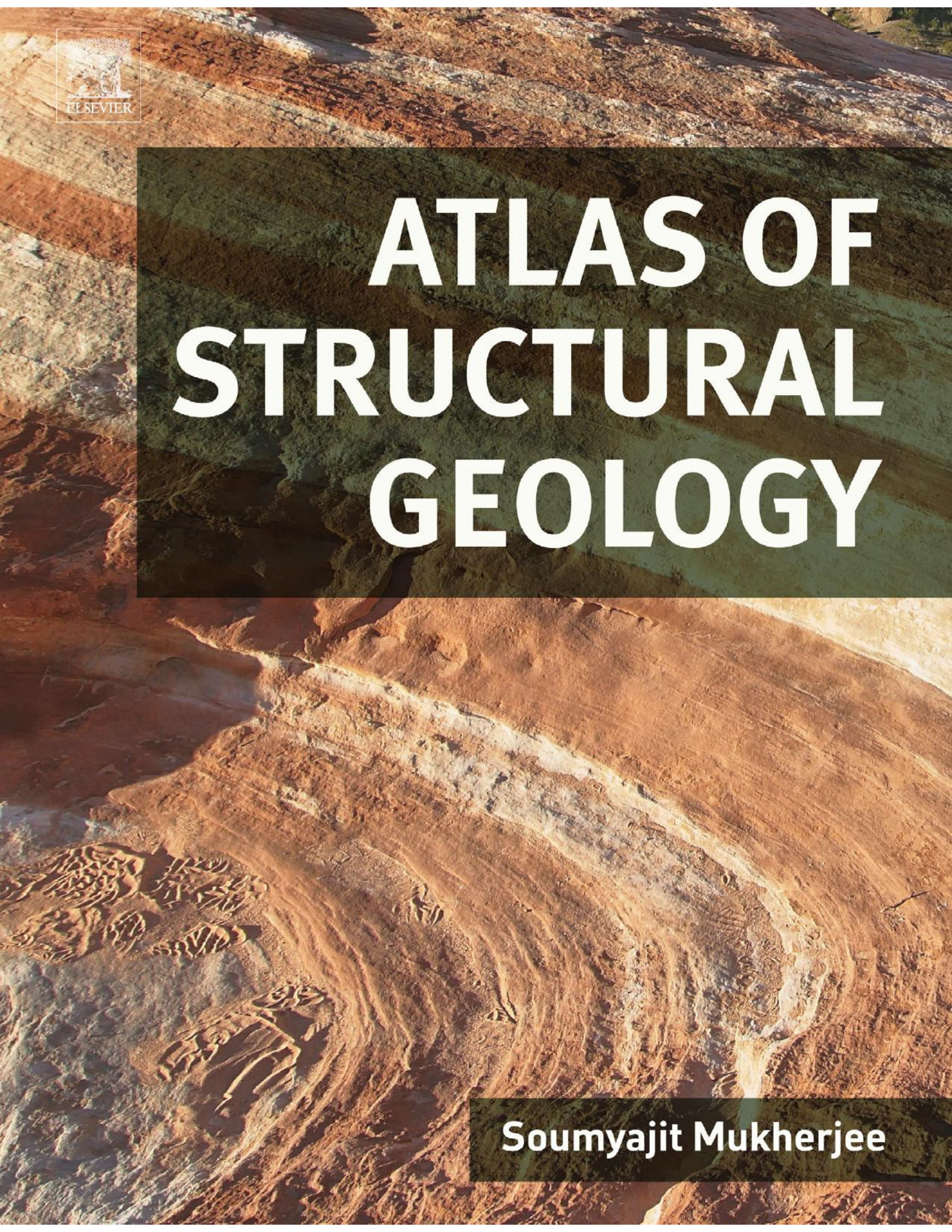

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ATLAS OF STRUCTURAL GEOLOGY

Soumyajit Mukherjee

Atlas of Structural Geology

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Atlas of Structural Geology

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Preface

Documentation of structures in different scales is the first step in many structural geological studies. This edited atlas gives an overview of diverse structures. Due to lack of space or inappropriateness, sometimes interesting structural snaps cannot be published in journals. This book fills that gap.

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Chapter 1

Folds

KEYWORDS
Folds; Folds not related to shear zones; Overturned fold; Shear zone related fold; Sheath fold; Superposed fold.

Two of the most intensely studied aspects in structural geology are morphology and genesis of folds (see Ramsay, 1967; Hudleston and Lan, 1993; Ez, 2000; Harris et al., 2002; Harris, 2003; Alsop and Holdsworth, 2004; Mandal et al., 2004; Carreras et al., 2005; Bell, 2010; Hudleston and Treagus, 2010; Godin et al., 2011; Harris et al., 2012a,b; Llorens et al., 2013; Mukherjee et al., in press). Of particular importance is whether folds found inside ductile shear zones are related to ductile shear (e.g., Mandal et al., 2004; Carreras et al., 2005; Bell, 2010). This chapter presents folds of different geometries and generations, some related with ductile shear zones, from different scales (Figures 1.1–1.87).

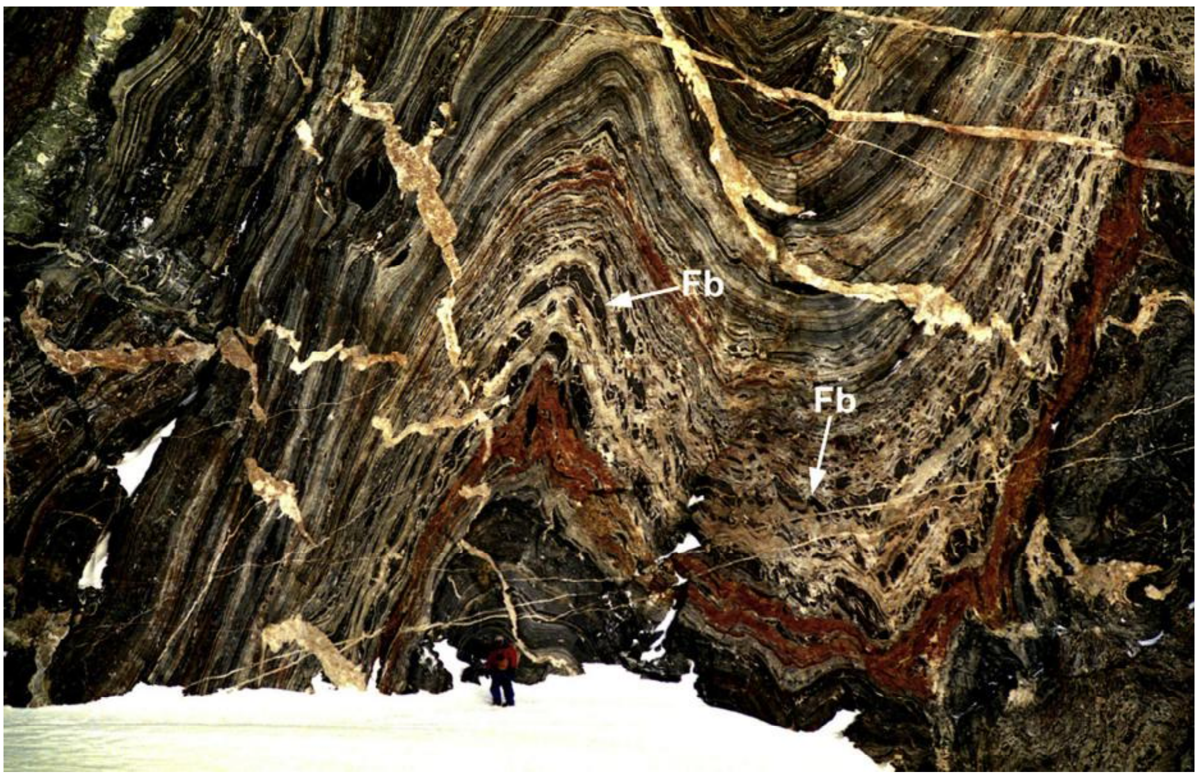

FIGURE 1.1 **Upright folds and folded boudins resulting from continental collision of East and West Gondwana.** The boudins of dark-colored amphibolite (Fb) in light-colored biotite-hornblende gneiss have originally pancake shapes with flattening parallel to compositional layering of gneiss, and resulted from the layer-parallel extension and thinning of crustal rocks within 640–600 Ma (Toyoshima et al., 1995). The folds with wavelengths of 20–30 m are parasitic upright folds of larger-scale upright fold related to 600–560 Ma sinistral transpression and crustal shortening during the collision (Toyoshima et al., 2013). The boudins (Fb) folded by the parasitic folds suggest that the tectonic regime changed from layer-normal to layer-parallel compression (Toyoshima et al., 2013). Osanai et al. (2013) presented SHRIMP U–PB ages for metamorphic rocks from the Sør Rondane Mountains, East Antarctica, and recognized periods of ultrahigh-temperature metamorphism (pre-main metamorphic stage) during 750–700 Ma and granulite- to amphibolite-facies metamorphism during 640–600 Ma. Location: 72°09′42″S, 25°31′50″E, the southern part of Salen in the Sør Rondane Mountains, East Antarctica. *(Tsuyoshi Toyoshima, Masaaki Owada, Kazuyuki Shiraishi)*

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Chapter 2

Ductile Shear Zones

KEYWORDS
C-plane; Couette flow; Ductile shear zone; Flanking structure; Mineral fish; Primary shear (C) plane; Pure shear; Shear; Simple shear; Synthetic secondary shear plane.

"Tabular or sheetlike, planar or curviplanar zones in which rocks are more highly strained than rocks adjacent to the zone" are called ductile shear zones (Davis et al., 2012; also see Mukherjee and Biswas, 2014; in press). Identification and study of ductile shear zones (Figures 2.1–2.55) are important since major plate boundaries are defined by such shear zones (Regenauer-Lieb and Yuen, 2003). We need to study such zones since along them partially molten rocks can flow (review by Clark et al., 2011). Secondly, viscous dissipation related to such zones has been investigated (Nabelek et al., 2011). No slip boundary condition was assumed classically to explain kinematics of ductile shear zones (Ramsay 1980; Mukherjee 2012; etc). However, recently, slip boundary condition is more recognized (Frehner et al., 2011; Mulchrone and Mukherjee, submitted). The ductile shear sense/sense of movement from such zones can be deciphered mainly from asymmetric sigmoid, parallelogram and lenticular clasts and intrafolial folds (Lister and Snoke, 1984; ten Grotenhuis et al., 2003; Mukherjee, 2011a,b, 2013a,b,c, 2014a,b,c; Bhadra and Gupta, in press). See Passchier and Trouw (2005) for review on ductile shear zones, and Mukherjee and Mulchrone (2013) and Mulchrone and Mukherjee (in press) for shear heat pattern in these zones. In addition to such shear sense indicators, this chapter also presents near symmetric clasts that form possibly within shear zones but that do not give the shear sense.

FIGURE 2.1 **Domino style normal faults with strike slip component, dipping 50° toward N60°–64°E (rake 70ºW).** Upper Pliocene–Lower Pleistocene polymictic volcanic breccias. A transtension component with western extension, is likely due to the parallelism of the Cordillera with the NW-trending Middle America trench located ~160 km to the W. The Cordillera de Tilarán is an andesitic extinct volcanic range, a paleoarc genetically associated with the Costa Rica subduction zone. There most of the ongoing and recent maximum and minimum horizontal stress are generated. Campos de Oro Arriba (10º22′4.09″N – 84º54′57.77″ W), Guanacaste Province, Costa Rica. See Dabrowski and Graseman (2014) as a latest paper on domino type structure. *(Guillermo Alvarado Induni)*

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Chapter 3

Brittle Faults

KEYWORDS
Brittle shear zone; Brittle tectonics; Conjugate faults; Faults; Kinematic indicators; P-plane; Slickensides; Y-plane.

Brittle shear zones/fault zones are usually defined by curved brittle P-planes bound by usually straight Y-planes (Passchier and Trouw, 2005). These shears may affect as a narrow zone within the rock bodies (Misra et al. 2015). Brittle sheared lenses of rocks vary in geometry, and the P-planes may curve only near the Y-planes (Mukherjee, 2014a,b). Fault gouge zones sometimes contain P-planes that help to deduce the shear sense. Fault planes/Y-planes may contain slickensides. See Doblas (1998) for detail of slickenside types and their reliable use in shear sense determination. This is despite Tjia (1964) questioned reliability of slickensides as shear sense indicators. Deformational structures and especially faulted units within soft-sedimentary structures are quite common (Byrne, 1994) (Figures 3.1–3.49). In collisional tectonic regimes, brittle faults can form either in an in-sequence or in an out-of-sequence manner (Mukherjee, in press).

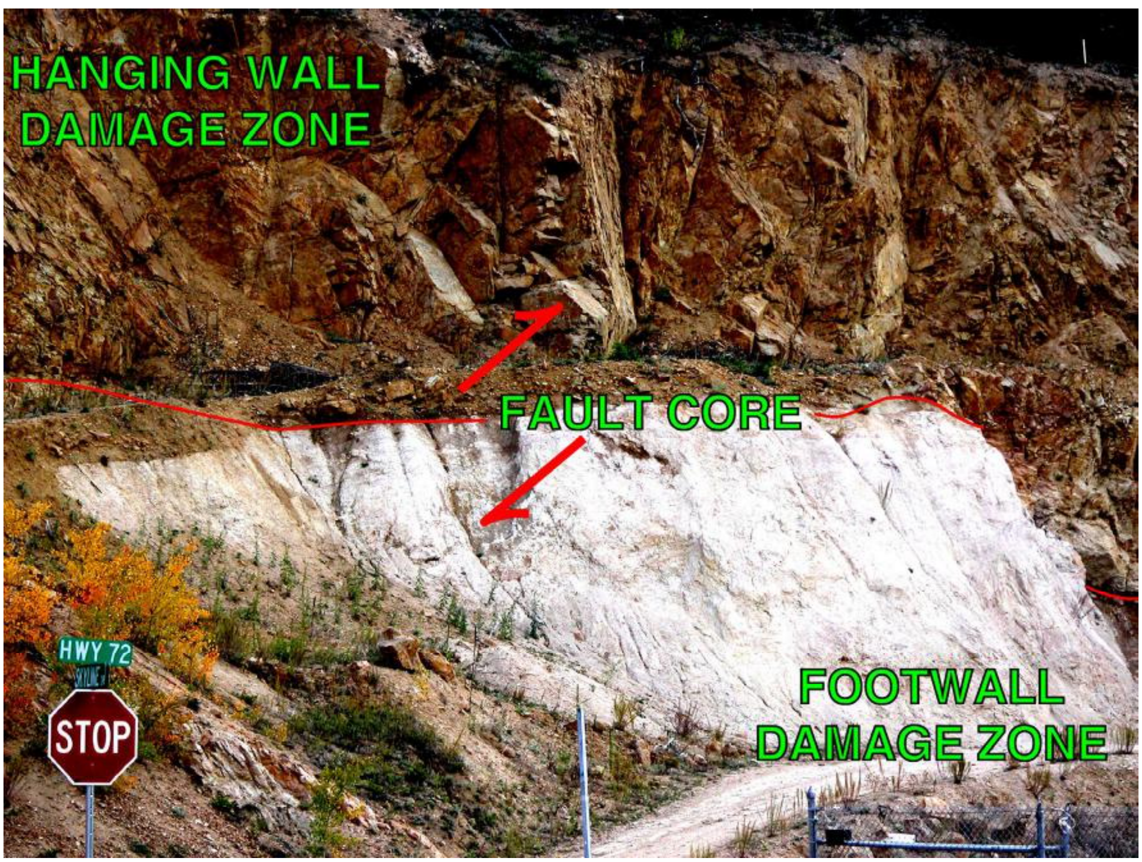

FIGURE 3.1 **Road-cut exposure of the Coal Creek fault zone, central eastern Front Range, Colorado, USA (39°54′14″N, 105°20′46″W).** This reverse fault zone occurs within the 1.7 Ga Boulder Creek, granodiorite batholith and hosts ~620-m west directed slip. The exposure shows a discrete, clay-rich gouge fault core and surrounding damage zone (cf. Caine et al., 1996). The damage zone is characterized by relatively low-temperature hydrothermal alteration concentrated mainly in hanging wall fractures juxtaposed against the pervasively and moderately altered clay-rich, white footwall. See Caine et al. (2010) for details. *(Jonathan Caine)*

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Chapter 4

Boudins and Mullions

KEYWORDS
Boudins; Mullions; Pinch and swell structures; Scar folds.

Local brittle–ductile extension partially or completely separate clasts. These segmented clasts are called boudins. Asymmetric boudins can be used to decipher shear sense (Goscombe et al., 2004). See Abe et al. (2013) for fracture patterns in boudinage. Mullions are *linear fluted structures developed within a rock or at lithological interfaces* (Twiss and Moores, 2007). Depending on their geneses, Twiss and Moores (2007) classified them into three types: "fold mullion," "fault mullion," and "irregular mullion." Viscosity contrast between the boudinaged/mullion material and the host rock is one of the controlling factors of their geometries (Sokoutis, 1990; Talbot, 1999; Schmalholz et al., 2008; Schmalholz and Maeder, 2012). Maeder et al. (2009) used the term "segment structure" to describe boudins and mullions together (Figs. 4.1–4.18). Mukherjee (2014a,b) reviewed terms to describe boudins in the light of flanking structures.

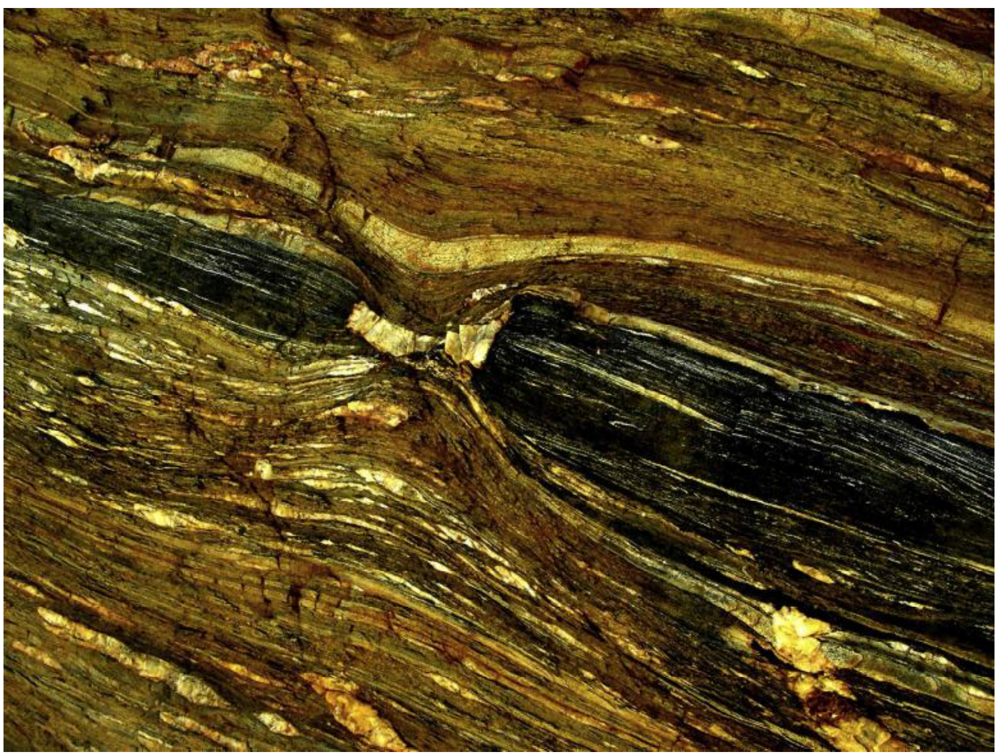

FIGURE 4.1 Photograph from the Gaub Canyon, Namibia, showing a boudinaged metabasalt layer enveloped by metaturbidites in the Southern Marginal Zone of the Damara Belt. The rocks deformed during Neoproterozoic to Cambrian, Pan African assembly of Gondwana (e.g., Barnes and Sawyer, 1980), with peak metamorphic conditions in the amphibolite facies. The rock assemblage comprises metamorphosed basalt, sandstone, mudstone, and chert, which represent intercalated continental and oceanic materials that were likely deformed in an accretionary prism (Kukla and Stanistreet, 1991). The photo highlights the rheological contrasts that develop through intercalation of lithologies of variable viscosity. In this case, the basaltic layer has fractured in the boudin neck, allowing formation of a quartz vein, whereas metasediments are locally folded to fill the gap between boudins of metabasalt. This provides an example of mixed brittle–viscous deformation at temperatures in excess of the brittle to viscous transition in quartzofeldspathic rocks, and a possible geological analogue to the mixture of transient creep and episodic brittle failure inferred to be responsible for deep tremor and slow slip in active subduction zones (Fagereng et al., 2014). Photo width: ~2 m. *(Ake Fagereng)*

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FIGURE 5.8 **Quartz vein network defined mainly by two sets of veins.** The set of veins dipping toward left are usually thicker than that dipping toward right. Chitradurga district, Karnataka, India. *(Aabha Singh)*

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Chapter 6

Various Structures

KEYWORDS
Columnar joints; Crater; Fissures; Fractures; Pull apart structure; Spheroidal weathering; Xenoliths.

This chapter presents various structures some of which are not worked intensely by structural geologists. Grain boundary migration in rocks observed under optical microscope can constrain the temperature the rock underwent (Stipp et al., 2002). Stability of buildings and fracturing during earthquakes has been a research topic to geoscientists (Krishnan et al., 2006). Study of faults and other structures has helped geoscientists to paleohydrology (Treiman, 2008) (Figures 6.1–6.60).

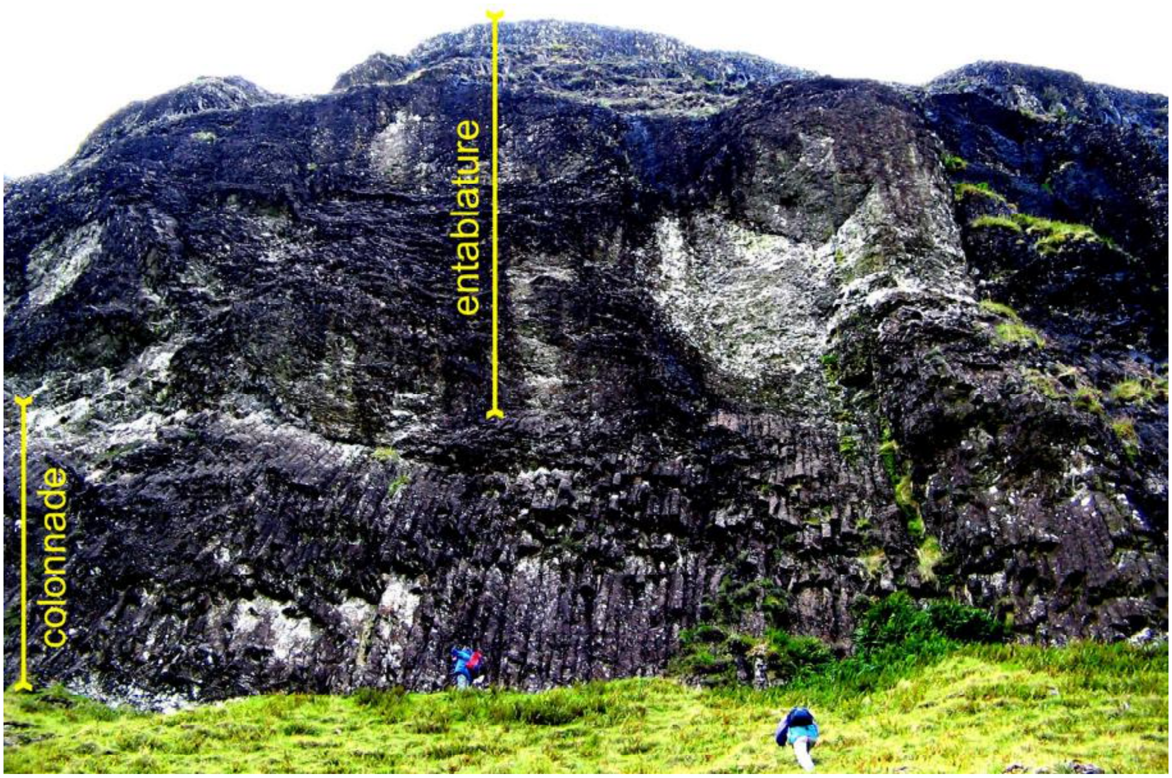

FIGURE 6.1 **Columnar joints, colonnade and entablature.** Thick solidifying lava flows develop contraction fractures that propagate from their cooling margins toward hotter interiors. These fractures, called columnar joints, divide a lava flow into columns, with polygonal (ideally hexagonal) shapes in plan. A subhorizontal basaltic lava flow of the Talisker Bay Group, Isle of Skye, Scotland is shown in the figure. The lower part of the flow shows well-developed vertical columns, suggesting nearly horizontal isotherms (contours of constant temperature within the lava flow). Such a columnar tier is called a colonnade. The upper part of this flow shows a highly chaotic and distorted internal structure, as would develop during rainfall or stream flow supplying water into the cooling flow interior and disturbing isotherms. This tier is known as an entablature. The colonnade and the entablature, though with greatly different field appearance, are part of a single lava flow. Here, the combined thickness of both is 120 m. *(Hetu Sheth)*

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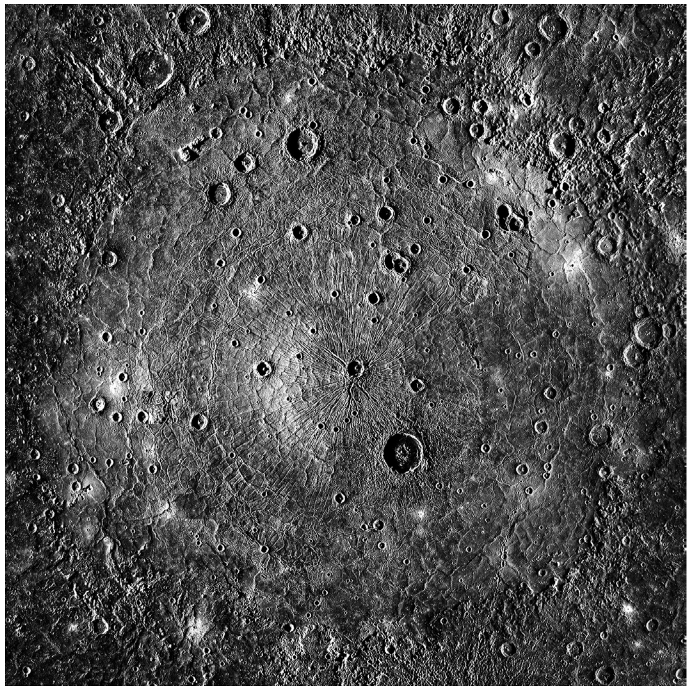

FIGURE 6.60 **The Caloris basin is the largest preserved impact structure on Mercury.** With an E–W diameter of 1640 km, the floor of the basin subtends ~40° of arc. The interior of the basin, which has been filled with voluminous, low-viscosity lavas, is replete with both contractional (wrinkle ridges) and extensional (graben) structures. The origin of these structures is not clear. The graben may have formed by thermal contraction of the interior lavas, similar to what is observed within Goethe basin, for example. Yet the pronounced radial orientations of the innermost graben are yet to be explained. The wrinkle ridges may be the result of subsidence of the Caloris interior lavas; however, in many places they remained active after the graben, and so could be due to the sustained global contraction of Mercury as its interior cooled. The image is in an orthographic projection centered at 31.5°N, 162.7°E. (Image credit: NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington). *(Christian Klimczak, Paul K. Byrne)*

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